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Influence of Clouds and Pollution in the Arctic Region: Some Characteristics of Short- and Long-Wave Radiation at Resolute, Northwest Territories, Canada

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On INFLUENCE OF CLOUDS AND POLLUTION IN THE ARCTIC REGION: SOME CHARACTERISTICS OF SHORT- AND LONG-WAVE RADIATION AT RESOLUTE, NORTHWEST TERRITORIES, CANADA

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SOME CHARACTERISTICS OF SHORT- AND LONG-WAVE RADIATION AT RESOLUTE, NORTHWEST TERRITORIES, CANADA

ABSTRACT

The influence of pollution on short-wave and long-wave radiation was investigated using data from synoptic observations for several years at Resolute (74°41'N, 94°55'W). The pollution factor in this study is defined as the difference between observed and calculated radiation at the ground. The pollution can, therefore, consist of dust, ice crystals, or other admixture to the atmosphere which does not appear as clouds.

Depletion factors for short-wave radiation of 0.04 to 0.06 were found, with a marked increase toward late summer, probably caused by different air mass characteristics. Marked diurnal variations were found in the depletion factor.

Because of the uncertainty in the temperature of the emitting surface, the influence of pollution on long-wave radiation could only be established for the case of ice crystals in the air, a common Arctic phenomenon.

The influence of ice crystals on the radiation budget was found to be quite substantial, between 3 and 22 percent of the radiation budget. Considering the great frequency of occurrence of ice crystals in Arctic winter conditions, it becomes apparent that the consideration of this pollution factor becomes essential for the energy budget of these areas.

SOME CHARACTERISTICS OF SHORT- AND LONG-WAVE RADIATION AT RESOLUTE, NORTHWEST TERRITORIES, CANADA

INTRODUCTION

Radiation calculations are generally based on the observed distribution of temperature, carbon dioxide, and water vapor in the atmosphere. The impurities of the air, which have an influence on radiation as well, are usually taken into account for short-wave radiation, but little is known whether this depletion goes into scattering or absorption. No attempt is usually made to consider the influence of the impurities on long-wave radiation.

The main difficulty lies in the fact that these impurities are rather inhomogeneous. They may be dust of all sizes and diversified material. The pollution over cities, which can no longer be regarded as merely a microclimatological problem, will be quite different from the pollution originating from grass fires over tropical and subtropical steppe and savanna areas and which cover vast areas. Quite different are condensation products, which are not recognized as clouds. The most outstanding of these are ice crystals, or "diamond dust," which is a common phenomenon in polar climates in winter. The basal layers observed under high wind conditions over the ocean are probably similar. In the following, the term pollution is applied irrespective of the type of material involved.

If it could be expected that in the foreseeable future the radiation observation network would be sufficiently widespread to dispense with calculated radiation values, it would hardly be worthwhile to investigate the problem. However, surface observations will at best cover only the land areas, that is, about 30 percent of the total area of the globe, and the present network observes probably not more than 5 to 10 percent of the incoming energy. Satellite observations, even if available on a routine basis, can give only the energy received and emitted from the system as a whole, while for many meteorological considerations a distinction is required between energy absorbed or emitted from surface and atmosphere. It seems necessary, therefore, to obtain some evidence about the influence of pollution on the different radiation components.

A station where the relevant radiation parameters at the surface and all other meteorological elements required for the theoretical calculation of the radiation terms are observed is necessary for this. The required radiation parameters are direct short-wave radiation, diffuse short-wave radiation, and reflected radiation. Additionally, for long-wave radiation the parameters include net radiation, hourly cloud observations, radiosonde ascents, visibility and weather. Unfortunately, these conditions are satisfied only at a very limited number of stations. One of these is Resolute, N.W.T., Canada (74°41'N, 94°55'W), at which hourly synoptic observations, hourly radiation observations for short-wave and total radiation, and twice-daily radiosonde ascents are made. The data for this station from 1961 to 1965 were used for short-wave calculations, and from 1964 to 1966 for long-wave calculations. The following procedures were used for the determination of the influence of pollution on radiation.

SHORT-WAVE RADIATION

The short-wave radiation as observed by an instrument at the surface can be obtained from the following equations:

$$SDR = SE \times FO_3 \times FH_2O \times FSC$$

$$SDF = SE \times FO_3 \times FH_2O \times 0.5\ FSC$$

$$SR = (SDR + SDF) \times A \times FH_2O \times 0.5\ FSC,$$

where

SDR = Direct solar radiation

SE = Extraterrestrial solar radiation with given solar elevation

FO_3, FH_2O, FSC = Depletion factors due to ozone and water vapor absorption, and scattering, respectively

SDF = Diffuse solar radiation

SR = Diffuse backscattering from albedo-induced radiation

A = Albedo.

The required quantity is then given by:

$$S_{calc} = SDR + SDF + SR.$$

For absorption and scattering coefficients Houghton's values were used. The calculations were carried out in detail by a method described by Vowinckel and Orvig (1968).

The required H_2O concentration was obtained from the twice-daily radiosondes, using a linear interpolation to obtain the hourly values. The required albedo values were obtained from the observed short-wave radiation and the observed reflected radiation. As the albedo determinations from these observations become unreliable with low solar elevations, when the resulting albedo may exceed 100 percent, only hours with solar elevations greater than 25° were used.

Furthermore, since even short-term occurrence of clouds had to be excluded, it was stipulated that clouds be absent throughout the hour of observation, and also one hour before and afterward. No daily observations were available for ozone and, hence, mean monthly ozone amounts after Pressman (1954) were used for the calculation of FO_3.

It must be expected that any influence on short-wave radiation not considered so far will be air-mass dependent, as is the case for the influences already described. Therefore, all results presented below are expressed as depletion factors valid for optical air mass 1.

Results

A comparison between the calculated and observed values showed that these values are not identical but that the observed values are systematically lower. In the 154 pairs of values only two were found where $S_{obs} = S_{calc}$, and none with $S_{obs} > S_{calc}$. The calculated values also showed a significantly smaller spread than the observed ones.

It could be considered that the inequality of S_{obs} and S_{calc} is the result of an incorrect absorption factor for either H_2O or CO_2. However, if this were the case, the magnitude of the inequality should either be constant, as in the case for CO_2, or a factor variable with the water vapor content of the air. Neither of these possibilities was found valid, and it is concluded, therefore, that this additional depletion is caused by dust or, more generally, by pollution.

The following average pollution factors were obtained by averaging all available observations for a month for 2° solar elevation intervals.

Month	Solar Elevation 26°	28°	30°	32°	34°	36°	38°	Average
June	---	0.0430	0.0367	0.0244	0.0317	0.0346	0.0762	0.0386
July	0.0413	0.0317	0.0391	0.0453	0.0475	0.0865	---	0.0451
August	0.0497	0.0629	0.0949	---	---	---	---	0.0612

The average value of the pollution factor nearly doubles from June to August, indicating a climatological increase in pollution during summer. This is to be expected, however, because the level of pollution will be higher over snow-free than over snow-covered ground, and over dry ground than over wet ground, because of the turbulence.

This distribution is apparently the result of the appearance, during summer, of a different air mass which is significantly more polluted, as shown by the following frequency distribution of the pollution factor for 28° solar elevation:

Month	Pollution Factor < 0.03	0.04-0.06	> 0.07
July	67%	24%	9%
August	33%	33%	33%

While in July rather clear air with a pollution factor of less than 0.03 is dominant, in August one-third of the cases were characterized by high pollution values. This means that either the source of polluted air in August is nearer to Resolute, or the circulation is such that a different type of air mass is predominant in August. Both factors probably work together.

Considering the values for the different solar elevations, a very sharp maximum of depletion of solar radiation is apparent in all three months at the highest solar elevations, i.e. near noon, and secondary maxima occur near the lowest elevation. As it is possible that there exists a difference between forenoon and afternoon, all periods with continuous clear skies during the whole day or during the whole forenoon or afternoon were considered. The following pollution factors are obtained:

Month	Hours 0800	0900	1000	1100	1200	1300	1400	1500	1600
June	0.0766	0.0465	0.0393	0.0434	0.0762	0.0237	0.0060	0.0215	0.0099
July	0.0715	0.0471	0.0493	0.0546	0.0855	0.0419	0.0309	0.0240	0.0352

Two maxima are also apparent here, although the expected afternoon maximum does not appear. The recording instruments are located to the north of the station at Resolute. As the station is a major source of pollution, it seems reasonable to assume that the depletion factors from 1100 to 1200 hours are not representative, since the sun's rays have to penetrate through this abnormally polluted air. In agreement with this consideration also is the fact that the pollution factor for noon decreases with increasing solar elevation at noon, from 0.0762 in June to 0.0949 in August.

If these noon values are excluded, there remains a marked diurnal fluctuation of the pollution factor with a maximum in the morning and a minimum around 1400 to 1500 hours in the afternoon. It is unlikely that this can be caused by pollution in the air. If this were the reason, the pollution factor should actually be higher in the early afternoon. Two possibilities for an explanation exist:

(i) The depletion is mainly a factor of scattering on albedo of the pollution. Since the albedo of snow, cloud and water increases with decreasing solar elevations, this could be true for pollution as well and would explain the observed phenomenon. The dependence on the solar elevation would, however, be somewhat higher than the albedo dependence observed over the other surfaces mentioned.

(ii) During morning the major pollution is probably concentrated below an inversion or vertical temperature discontinuity, while this is probably not the case during early afternoon. It is possible that the optical properties of the pollution change, depending on whether it is in a dense layer or more evenly distributed over a thick air mass.

The data discussed may be compared with those quoted by Katayama (1966). He gives depletion factors of 0.03 for oceanic and 0.10 for continental air masses. Robinson (1963) gives values of 0.01 to 0.03 as pollution factors for stations with little pollution (Halley Bay, Lwiro, Pretoria, Windhoek).

It is apparent that the values obtained for Resolute are comparable to the calculations by other authors. But considering the location of Resolute in the far north, with rather wet surface conditions and no obvious source of pollution in its vicinity, except for the immediate area, the observed values are high and may be due, in part, to very small water droplets, which are not recognized as clouds, but which may be the main contributing factor to the pollution influence. From the frequency tables given it is apparent, however, that average values have only climatological significance, and that for individual days very large variations can be expected, which would certainly need further investigation, with more diversified data and especially an attempt to correlate the pollution factor to a synoptically-observed element.

It is also evident that local sources of pollution may have a very significant influence on the pollution factors and may indeed invalidate results from particular stations.

LONG-WAVE RADIATION

Data from Resolute for 1964-66 were used for the long-wave calculations. Again, only clear-sky conditions, defined previously, were used. Apart from cloud conditions the synoptic observations of present weather and wind force were considered. The calculated long-wave radiation was obtained by the method described by Kondratiev and Niilisk (1961). Ten levels were used for the calculations: surface, 950, 900, 850, 800, 700, 600, 500, 400, and 300 mb. The assumptions for the layer above 300 mb are described by Vowinckel and Orvig (1968). However, the higher layers are quite insignificant for $L\downarrow$ (long-wave radiation downward at the surface), since the bulk of this radiation originated in the lowest 2000 m.

Since long-wave radiation is much more sensitive to the upper air temperature and moisture conditions than short-wave radiation, only the hour before and after the ascent were considered. The total number of observations satisfying these criteria was 126.

The following radiation observations were available: net radiation, long- plus short-wave, and short-wave radiation absorbed, the latter being the result of incident short-wave minus reflected short-wave radiation measurements. The calculations of long-wave radiation give only L↓ (atmospheric long-wave radiation). To obtain RL (L↑ - L↓) an assumption has to be made about the temperature of the emitting surface, the active layer. Usually the screen temperature is used because of lack of temperature observations at the surface. This approximation was used as well in this investigation. The result is that the calculated R (radiation budget) will be too low during the time of no short-wave radiation and too high during daytime. At night the surface temperature will be lower than the screen temperature, and hence the emission will also be lower, so that in the calculation the negative term L↑ becomes too high, and R too low. The reverse is valid during daytime.

Results

The following figures give the mean difference between RC (radiation budget calculated) and RO (radiation budget observed) for clear-sky conditions with no short-wave radiation and no particular weather phenomenon for different wind speeds:

F (wind speed, mph)	0/1	2/3	4/5	6/7	8/9	10/11	Mean for 3 hours
△ RO - RC (cal/cm^2)	-2.7	-0.6	-1.7	-1.6	+0.4	-0.5	= -1.37

The distribution is not very smooth, because of the small sample, 48 observations. However, it is apparent from these figures that under calm conditions the surface temperature differs from the screen temperature by more than it would under windy conditions. It can be calculated that with calm weather the surface temperature is about 3° below the screen temperature, and with average windy conditions (mean of all observations with $F > 2$ mph) about 1°. These values are slightly higher than the ones reported from several authors by Vowinckel and Orvig (1964) for the Polar Ocean. This is expected because (1) over land the flux from below the surface is lower, and hence, the temperature difference is greater, and (2) any observation with a thermometer at the ground is likely to give somewhat unrepresentative values, since the emitting surface is very thin indeed and its temperature can only be measured accurately by radiative thermometry.

It is apparent from these considerations that a change in radiation caused by pollution cannot be verified by a comparison of RC and RO. However, if these differences are compared against conditions when the pollution is much higher than in the sample used in this study, the influence of this type of pollution can be established. The most readily available condition for the Arctic is the presence of ice crystals, code number WW = 76. The following figures give the values for D, where

$$D = (\text{RO clear} - \text{RG clear}) - (\text{RO } 76 - \text{RC } 76):$$

F (wind speed, mph)	0/1	2/3	4/5	6/7	8/9	10/11	Mean for 3 hours
D (cal/cm^2)	+0.16	-1.05	+0.04	-2.05	-2.40	-1.08	= -0.94

The figures show the marked influence of the presence of ice crystals. With an average of 33.7 cal/cm^2/3 hours on the days with WW = 76 the actual $L\downarrow$ is increased by 2.7 percent. If only conditions with wind force > 6 mph are considered, the mean $L\downarrow$ is 33.2 cal/cm^2/3 hours and the percentage increase is 6.3 percent. Since the net radiation is only a small residual of the large $L\uparrow$ and $L\downarrow$ terms, the percentage error caused by WW = 76 in the net is much larger, on the average 8.1 percent, and for $F > 6$ mph, 19.7 percent.

It is also noteworthy that the influence of ice crystals varies with wind conditions. With calm or little wind the presence of ice crystals tends to decrease the $L\downarrow$. The reason is probably that under these conditions the crystals are below the strong inversion, so that for the surface the radiation from the warmer, upper part of the atmosphere is decreased and from the colder part is increased. With higher wind forces and the absence of a strong inversion, especially with ice crystals in higher layers, the $L\downarrow$ is increased. It is apparent that the vertical distribution of the pollution is even more important for long-wave than for short-wave radiation.

Returning again to the figures for conditions without ice crystals, given above, we can use the likely, but not proved, assumption that with a wind force $F > 8$ mph no inversion of any significance exists, and hence the difference between calculated and observed values represents the real influence of pollution. This would give a pollution influence of 0.1 cal/cm^2/3 hours for clear-sky conditions without ice crystals, or 8 percent of the net radiation. It should be kept in mind, however, that this figure is only valid for clear sky and Arctic winter. With overcast conditions the influence of pollution will be quite different, depending on temperature, moisture conditions and height of the clouds. It is quite conceivable that under these conditions the influence would have a reversed sign.

Arctic winter is probably the time with least pollution in the air, and it would be desirable to also have figures for summer. However, the assumption that the screen temperature equals the surface temperature with $F > 8$ mph is not valid if short-wave radiation is present, as shown by the following figures for RO - RC for conditions with short-wave radiation:

F (wind speed, mph)	0/1	2/3	4/5	6/7	8/9
RO - RC (cal/cm^2/3 hours)	+9.9	+5.9	+4.9	+3.9	+2.0

The overheating of the ground seems to be directly dependent on the amount of short-wave radiation available, as shown by the next set of figures:

Short-Wave Radiation (cal/cm^2/3 hours)	1-5	6-10	11-15	16-20	21-25	26-29
RO - RC (cal/cm^2/3 hours)	-1.5	+2.0	+8.3	+12.9	---	+22.9

It is apparent that with the observations available daytime values cannot be used. Due to the timing of the radiosonde ascents no night-time observations were available during summer.

From the data used in the present investigation, only an approximation of the influence of pollution during winter can be given. Using pollution in its widest sense, i.e. regarding the ice crystals as a form of pollution, and using wind values of only 8 mph and over, the following frequency distribution of pollution influence is obtained:

R	+	+	+	+ -
RO - RC (cal/cm^2/3 hours)	> +2.6	2.5-1.6	1.5-0.5	0.5-0.5
Distribution (%)	6	3	3	12

R	-	-	-	-	-
RO - RC (cal/cm^2/3 hours)	0.6-1.5	1.6-2.5	2.6-3.5	3.6-4.5	> 4.6
Distribution (%)	22	15	12	18	9

The mean value being -1.9 cal, RO for these cases was -11.5 cal, so that the mean effect of pollution, in the widest sense, was 16.5 percent. It is also apparent from these figures that individual values may vary widely, even changing their sign. This unexpectedly high influence of pollution in the Arctic clear-sky winter is most certainly the result of the high frequency of ice crystals. Sixty-two percent of all observations used in this investigation showed ice crystals.

CONCLUSIONS

It is apparent from the discussion that pollution has a significant influence on the energy available at the ground. For short-wave radiation the influence is on the order of a few percent, but is highly variable with season, weather pattern and solar elevation, and before more meaningful statements can be made, a larger set of data from different stations has to be evaluated.

For long-wave radiation the influence is much stronger and, under the predominantly clear-sky conditions of the polar winter, of great significance. But here even more observations and possibly a breakdown of $L\downarrow$ into different layers is required to obtain a better understanding of the processes.

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